

Study of a liquid-piston traveling-wave thermoacoustic heat engine with different working gases



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ABSTRACT

Thermoacoustic technology is becoming increasingly attractive because of its high reliability and environmental friendliness. The double-acting traveling-wave thermoacoustic heat engine using liquid pistons, proposed by our group, can improve the thermoacoustic conversion efficiency further and yield a more compact engine. In this study, three different environmentally friendly working gases, helium, nitrogen and carbon dioxide, were studied experimentally, primarily in terms of thermoacoustic conversion parameters, including the onset temperature, the resonant frequency, and the pressure ratio, under different working mean pressures. Results show that the working gas significantly influences thermoacoustic performance. They also suggest a very encouraging application prospect for this novel thermoacoustic heat engine. Finally, we performed theoretical analysis to better understand thermoacoustic conversion with the different working gases.

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1. Introduction

Environmental impact and energetic efficiency have become central concerns of energy production in recent years. Modern internal combustion engines consume large amounts of gasoline, coal, and other non-renewable resources. The resulting air pollution is both harmful ecologically and unsustainable in the long term. Thermoacoustic heat engines are a kind of external combustion engine with a highly variable heating temperature, potentially amenable to exploiting low-grade heat sources like industrial waste heat or solar energy. The working gas in such engines (e.g., helium or nitrogen) is also eco-friendly. The engines are relatively more durable, thanks to having no moving parts.

Our novel double-acting traveling-wave thermoacoustic engine with liquid pistons (Fig. 1) can improve the thermoacoustic conversion efficiency further, allowing more compactness and better load matching [1], when compared with traditional thermoacoustic engines. By using gas–liquid coupling vibrations [2], it greatly enhances the pressure amplitude, and effectively reduces the resonant frequency. Each heat engine unit in the looped, double-acting system requires no phase-adjusting device and can operate in an ideal acoustic field [3].

In a thermoacoustic system, the working gas not only serves as a carrier for transferring and storing heat and acoustic energy, but is also the key component of the thermoacoustic conversion process [4]. The heat penetration depth and the viscous penetration depth of the working gas play important roles in the conversion processes: the former for driving the thermoacoustic effect, and the latter for dissipating kinetic energy. Reducing the viscous penetration depth and increasing the heat penetration depth in this manner can improve the overall efficiency. The ratio between these two penetration depths varies as $Pr^{1/2}$, and therefore the gas used in the working medium should have a low Pr [5]. Another way to improve the efficiency is to use a working gas with a small speed of sound. For these reasons, helium, nitrogen and carbon dioxide have been widely used in thermoacoustic systems, and their performance parameters are listed in Table 1.

This study examined these three environmentally friendly working gases experimentally, focusing on a few specific thermoacoustic conversion parameters: the onset temperature, the resonant frequency, and the pressure ratio, under different working mean-pressure conditions. The results show that the working gas has a significant influence on the thermoacoustic performance, and theoretical analysis compared thermoacoustic conversion based on the different working gases. Each of the three working gases has advantages and disadvantages, and the best working gas therefore depends on the particular application considered.

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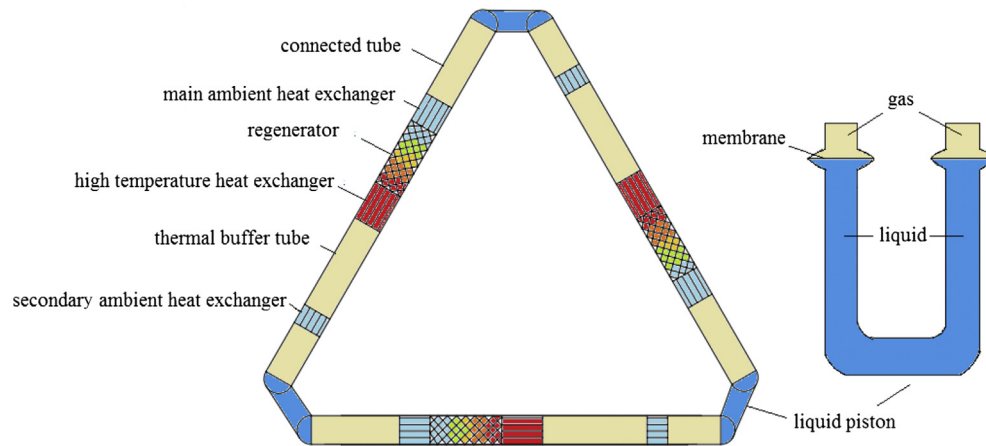


Fig. 1. Schematic diagram of the liquid-piston travelling-wave thermoacoustic heat engine.

2. Experimental device

The experimental device of the double-acting traveling-wave thermoacoustic engine with liquid pistons is shown in Fig. 2. The diameter of each component is 50 mm, and the designed heating power, the designed output acoustic power, and the mass of water in a single engine are 3 kW, 1 kW and 3 kg, respectively. During the experiments, the heating temperature was measured by nickel–chromium/nickel–silicon sheathed thermocouple, the mean pressure by a piezoresistive pressure sensor (Kunlun Coast, Beijing), and the oscillating pressure by another piezoelectric pressure sensor (PCB Piezotronics, Inc.).

To reduce vibrations and for safety reasons, the engine was suspended during the experiments and the new U-type resonator with a membrane, shown in Fig. 3, was used. This resonator design completely isolates the gas and the water and controls the DC in the

loop [6]. As the length of the air tube remained constant, the engine was stable. We also increased the membrane cross-sectional area to reduce the displacement amplitude and to make the membrane more durable.

Each gas used in the thermoacoustic process has its optimal relative hydraulic radius [7]. The appropriate regenerator hydraulic radius must be chosen according to the characteristics of the working gas in order to optimize thermoacoustic conversion.

The initial design of the regenerator of this engine being destined for helium, we chose a 120-strand stainless-steel mesh, with a porosity of approximately 73%. Fig. 4 shows the regenerator and the stainless steel mesh. This setup is suboptimal for nitrogen or carbon dioxide, but we can nonetheless use it to analyze the effect of these gases on thermoacoustic performance. Future experimental studies will use regenerators with a structure size optimized for nitrogen, carbon dioxide, or any other working gas.

Table 1

Performance parameters of three working gases.

	Viscous penetration depth (10^{-5} m)	Heat penetration depth (10^{-5} m)	Pr	Speed of sound (m/s)
Helium	22.2	27	0.68	819
Nitrogen	7.98	9.44	0.71	345
CO ₂	6.02	7.54	0.64	286

3. Experimental results and analyses

3.1. Helium

Helium is a common working gas used in thermoacoustic systems because its large heat penetration depth and low Pr, together with a low boiling point, makes it the most suitable working

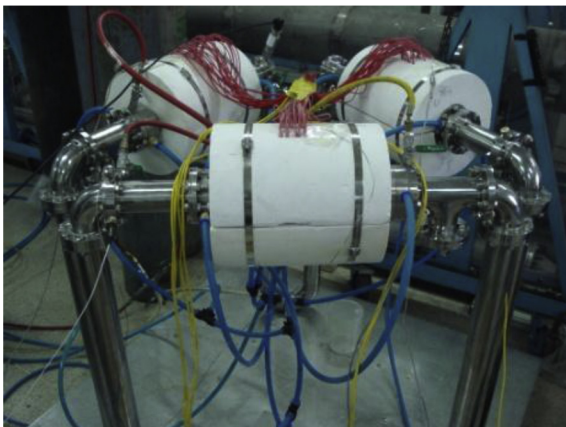


Fig. 2. Experimental system.

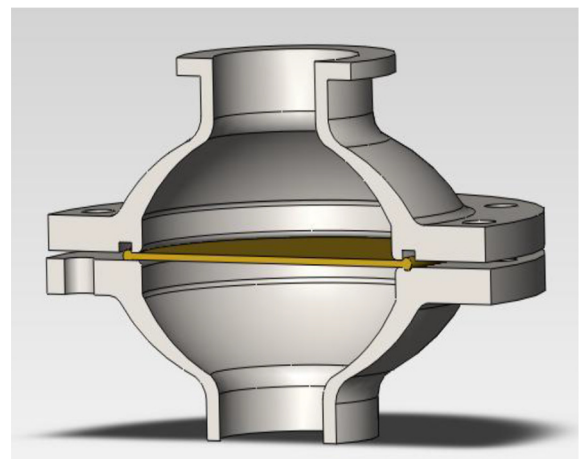


Fig. 3. Membrane configuration.

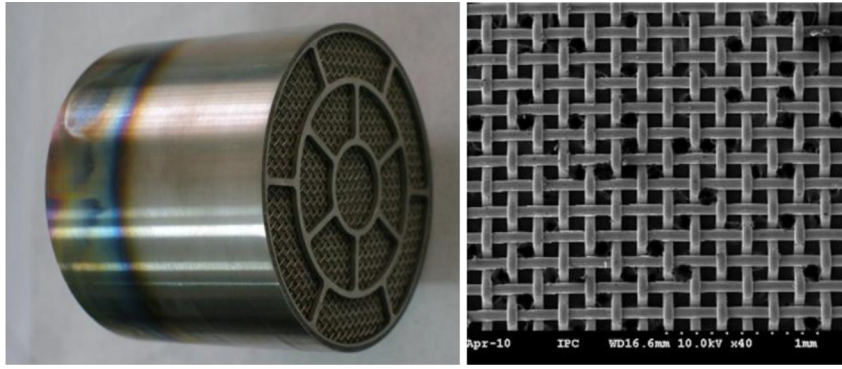


Fig. 4. The regenerator and the stainless-steel mesh.

medium for cryogenic thermoacoustic refrigeration. In addition, global helium reserves are scarce, making it a precious and expensive gas resource.

Fig. 5 shows the heating temperature as a function of the heating power, under different mean-pressure conditions, when helium gas is used. As the heating power increases, the heating temperature grows steadily for each pressure. For a mean pressure of 1.5 MPa and a heating power 1200 W, the heating temperature reaches 568 K. However, for a safer mean pressure of 4.0 MPa, the maximum heating power is only 700 W.

Fig. 6 shows the pressure ratio P_r as a function of the heating power for a range of mean helium pressures. Defining the pressure ratio $P_r = (P_0 + P_1)/(P_0 - P_1)$, P_r is an important parameter for measuring the performance of engines, i.e., their ability to drive an external load. It can be seen that P_r increases with the heating power. For a mean pressure of 1.5 MPa and a heating power of 1200 W, the heating temperature is 568 K and pressure ratio is 1.45, much greater than the 1.12 seen in the traditional thermoacoustic engine in our laboratory under the same heating temperature [8]. Clearly, the novel engine shows a significantly better performance.

3.2. Nitrogen

Nitrogen is commonly used in thermoacoustic heat engines because of its small viscous penetration depth and low operating frequency, and it is copiously and cheaply available.

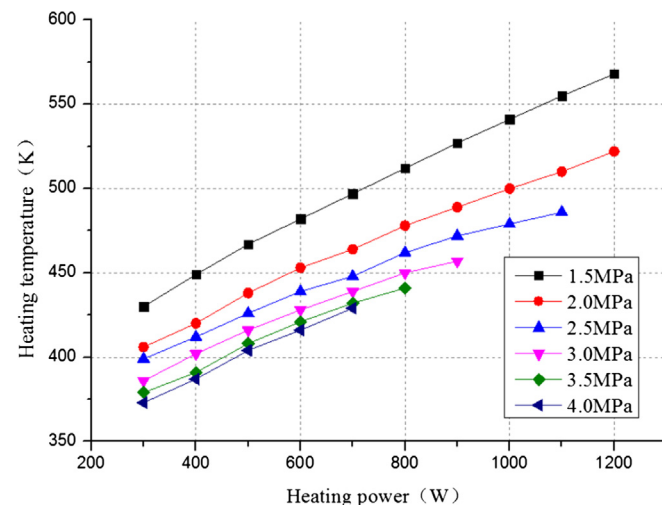


Fig. 5. Heating temperature vs. heating power using helium.

Fig. 7 shows the heating temperature as a function of the heating power for different mean nitrogen pressures. The heating temperature increases with the heating power. When the mean pressure is 2.5 MPa and the heating power is 1200 W, the heating temperature reaches 606 K.

Fig. 8 shows the pressure ratio as a function of the heating power for the different mean nitrogen pressures. The pressure ratio increases with the heating power. When the mean pressure is 2.0 MPa and the heating power is 1000 W, the pressure ratio is 1.30, a lower value than with helium.

3.3. Carbon dioxide

P_r for carbon dioxide is slightly greater than for nitrogen by 2%, and 24% smaller than for helium. The speed of sound in carbon dioxide is 76.5% of that in nitrogen and 26.5% of that in helium. So carbon dioxide is suitable for using in thermoacoustic heat engines. Experiments with carbon dioxide use a heating power below 800 W for safety reasons.

Fig. 9 shows the heating temperature as a function of the heating power for different mean carbon dioxide pressures. As the heating power increases, the heating temperature increases and is greater than the corresponding temperature with helium. For a mean pressure of 2.5 MPa and a heating power of 800 W, the heating temperature here reaches 533 K.

Fig. 10 shows the pressure ratio as a function of the heating power for different mean carbon dioxide pressures. The pressure

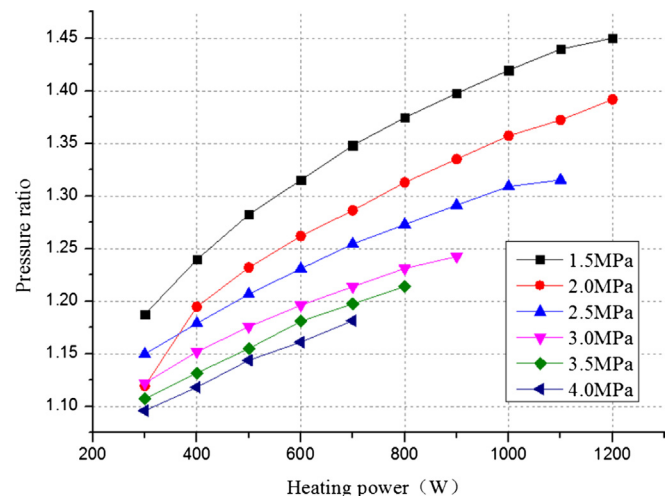


Fig. 6. Pressure ratio vs. heating power using helium.

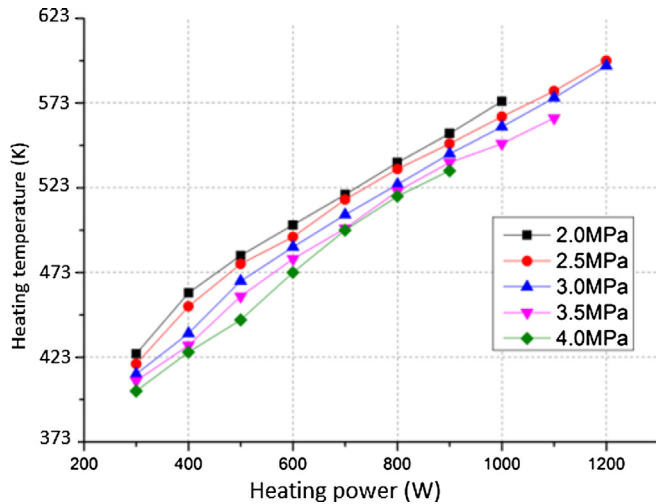


Fig. 7. Heating temperature vs. heating power using nitrogen.

ratio increases as the heating power grows. When the mean pressure is 2.5 MPa and the heating power 800 W, the pressure ratio is only 1.19, a lower value than with either helium or nitrogen.

3.4. Comparison of the three gases

The variations of the heating temperature and of the pressure ratio with the heating power, for different mean pressures of the different gases, were shown above. Other parameters, like the onset temperature, the resonant frequency and the oscillating pressure amplitude are also important for characterizing the performance of thermoacoustic engines [9], and we therefore also compared these engine parameters with the three working gases, with a view to determining the most appropriate gas for a given application.

Fig. 11 shows the change in the onset temperature, when the heating power is 300 W, as a function of the mean pressure for the three different gases. Carbon dioxide shows the lowest onset temperature, below 328 K at each pressure, making it more appropriate for applications with low-grade heat. The onset temperatures for helium and nitrogen are also lower than in a traditional traveling-wave thermoacoustic engine [10]; as the mean pressure increases, the onset temperature decreases. Thus, the

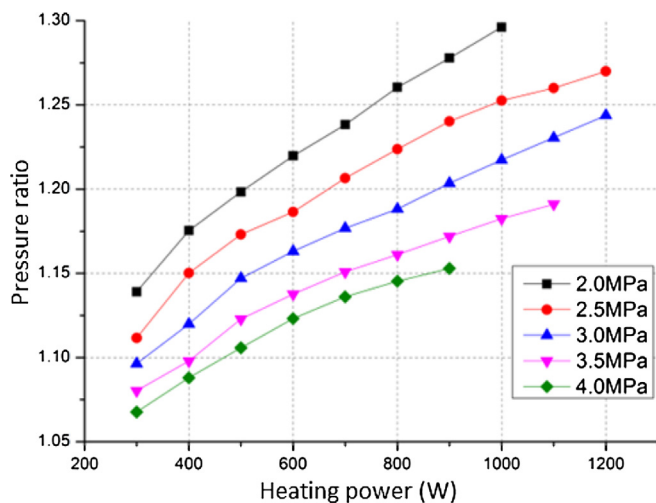
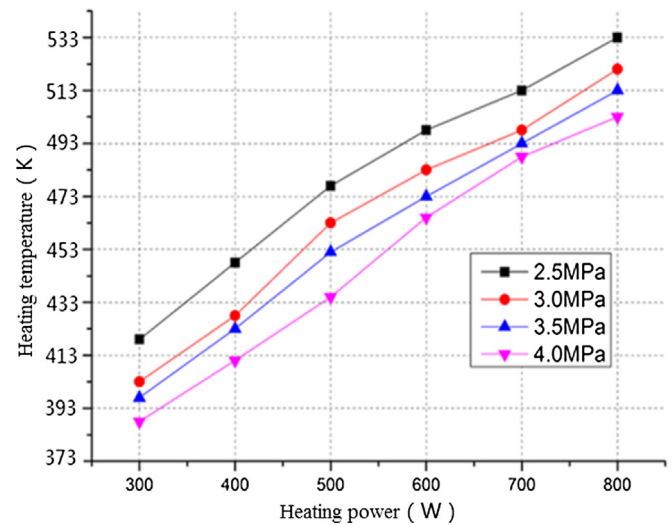


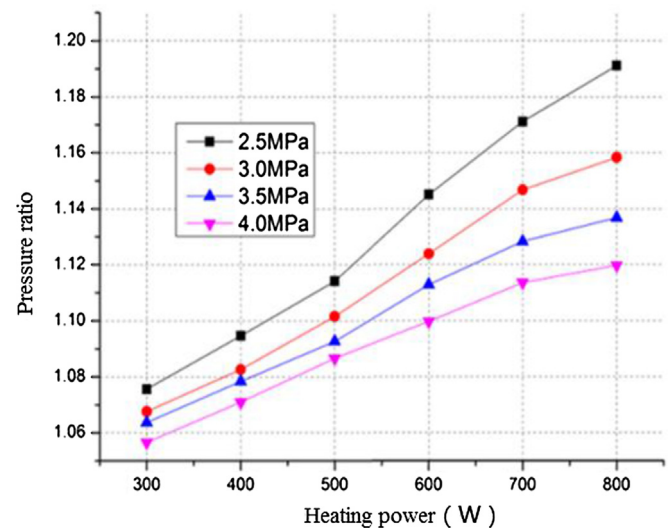
Fig. 8. Pressure ratio vs. heating power using nitrogen.

Fig. 9. Heating temperature vs. heating power using CO₂.

lower onset temperature is a significant advantage of the novel thermoacoustic engine with liquid pistons.

Fig. 12 shows, for a heating power of 800 W, the resonant frequency as a function of the mean pressure for the three gases. The resonant frequency increases monotonically with the mean pressure. For all pressures, the resonant frequency for nitrogen is lower than that for helium but higher than that for carbon dioxide. However, the difference is small because, in novel thermoacoustic heat engines with liquid pistons, the resonant frequency depends mainly on the mass of water (which in experiments is always 3 kg) and the length of the air tube (which remains constant). Compared with traditional engines, the novel thermoacoustic heat engine with liquid pistons has a lower resonant frequency, which helps to improve the efficiency and to drive low-frequency refrigerators or heat pumps [11].

Fig. 13 shows the oscillating pressure amplitude as a function of the heating power when the mean pressure is 3.0 MPa, for the different gases. The oscillating pressure amplitude increases continually as the mean pressure increases. For all heating powers, the values for nitrogen are lower than for helium but higher than

Fig. 10. Pressure ratio vs. heating power using CO₂.

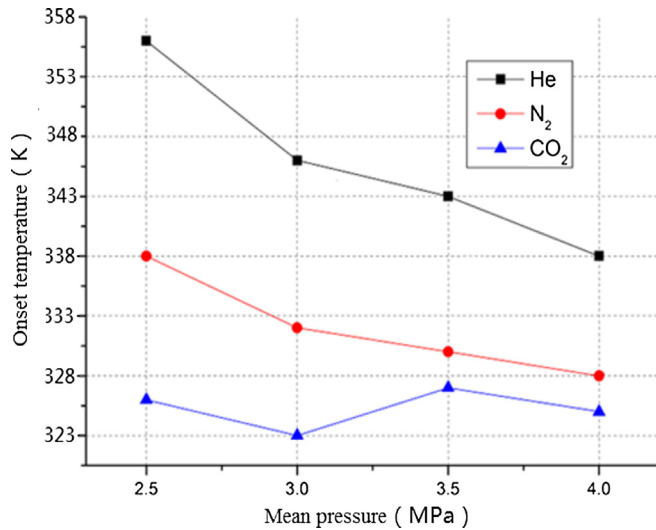


Fig. 11. Onset temperature vs. mean pressure for the different gases.

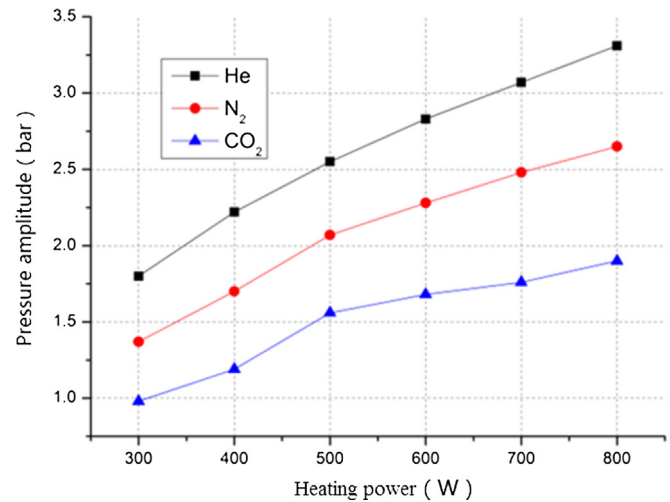


Fig. 13. Oscillating pressure amplitude vs. heating power with different gases.

for carbon dioxide. This is because the heating power could not be fully converted to acoustic power with nitrogen or carbon dioxide, for which the oscillating pressure amplitudes are consequently lower [12]. In simulation, we compared the performance of the engine under helium and nitrogen using each designed regenerator, and the results show that the performance of helium is also better [13].

Fig. 14 shows the heating temperature as a function of the heating power when the mean pressure is 3.0 MPa, for the three gases. The heating temperature increases continually with the heating power. The heating temperature for carbon dioxide is always higher than for helium and lower than for nitrogen because only when the gas is helium can the heating power be fully converted to acoustic power and the heating temperature is low. For a given heating power, though the acoustic power for carbon dioxide is the smallest, the heat penetration depth of carbon dioxide is smaller than nitrogen which means the heating power would be transferred to the regenerator worse, so the heating temperature for carbon dioxide is less than for nitrogen.

According to Table 1 and thermoacoustic theory, we can get the theoretical analyses of the experiments with three different gases.

In thermoacoustic engine using the gas with small speed of sound can reduce the frequency, so the resonant frequency for carbon dioxide is the lowest as it has the smallest speed of sound, highlighting the advantage of carbon dioxide. For a given heating power, the oscillating pressure amplitude is the largest and the heating temperature is the lowest for helium, which gives helium the highest thermoacoustic efficiency. That's because the heat penetration depth of helium is the largest, and the heat power can be easily transferred to the regenerator which is good for thermoacoustic conversion. However, helium is much more expensive than either carbon dioxide or nitrogen, and the use of carbon dioxide raises some ecological issues. In summary, all three gases have their own advantages and disadvantages, and their choice for future applications must be fully considered.

4. Conclusion

The choice of working gas in an engine does not only consider issues of energy and environmental friendliness, it also strongly determines thermoacoustic performance. In this paper, three different ecological working gases were studied experimentally,

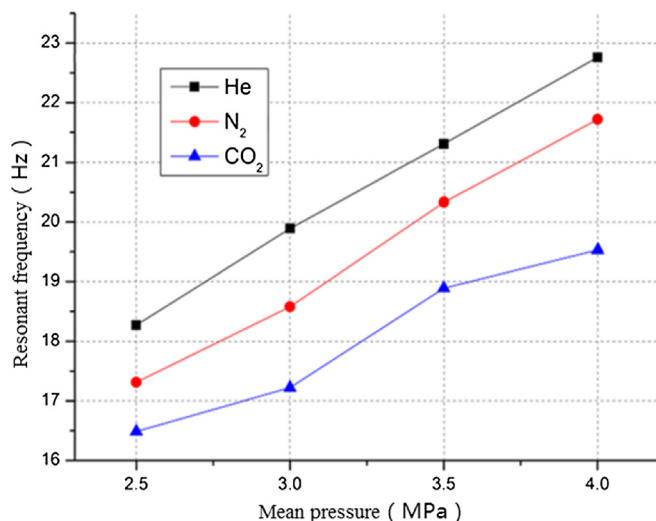


Fig. 12. Resonant frequency vs. mean pressure for the different gases.

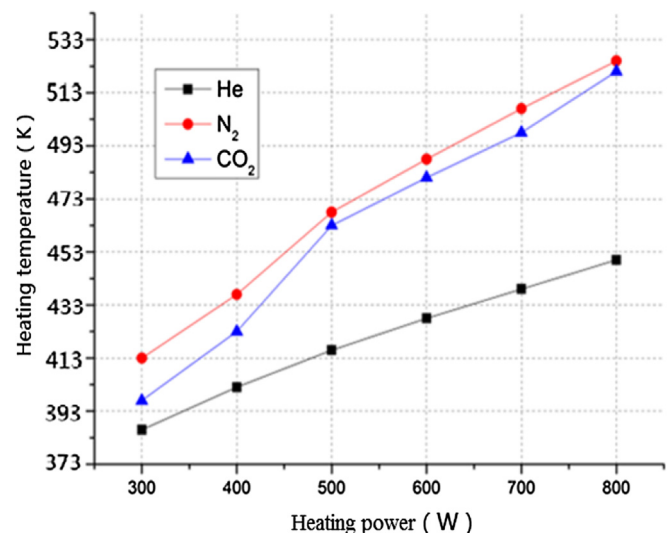


Fig. 14. Heating temperature vs. heating power with different gases.

helium, nitrogen and carbon dioxide, in terms of a few thermoacoustic conversion parameters.

The experimental results show that when the mean pressure is constant, the heating temperature and pressure ratio for all three gases improve as the heating power increases. Simultaneously, when the heating power is unchanged, both the heating temperature and the pressure ratio of the three gases decrease as the mean pressure increases. Compared with the traditional one, the performance of the novel engine has shown to be much better.

Comparing these three gases, the onset temperature of carbon dioxide is the lowest making it more appropriate for applications with low-grade heat and the resonant frequency of carbon dioxide is also the lowest because it has the smallest speed of sound. For a given heating power, the oscillating pressure amplitude for helium is the largest and its heating temperature is the lowest, which implies that the thermoacoustic efficiency with helium is the highest. That's because the heat penetration depth of helium is the largest, and the heat power can be easily transferred to the regenerator which is good for thermoacoustic conversion.

Helium is much more expensive than the other two gases, however, and the use of carbon dioxide has some environmental issues. In short, we should fully consider the choice of three different gases for future applications.

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